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HARNESSING SCIENCE AND TECHNOLOGY FOR SUSTAINABLE RICE-BASED PRODUCTION SYSTEMS

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Rice is the world's most important food crop and a primary source of food for more than half of the world's population. More than 90% of the world's rice is grown and consumed in Asia where 60% of the earth's people live. Rice accounts for 35 to 75% of the calories consumed by more than 3 billion Asians. It is planted to about 154 million hectares annually or on about 11% of the world's cultivated land.

Rice is probably the most diverse crop. It is grown as far north as Manchuria in China and as far south as Uruguay and New South Wales in Australia. Rice grows at more than 300 meters elevation in Nepal and Bhutan and 3 meters below sea level in Kerala in India. Rice growing environments are classified into four major categories e.g. irrigated, rainfed, upland and flood prone (Khush 1984). The categorization is based on several criteria such as water regime, drainage, soils and topography.

Major advances have occurred in food production during the last four decades due to adoption of green revolution technology. Between 1966 and 2000, the population of densely-populated low income countries grew by 90% but rice production increased by 130% from 257 million tons in 1966 to 600 million tons in 2000. In 2000, the average per capita food availability was 18% higher than in 1966. The technological advance that led to dramatic achievements in world food production during the last 40 years was the development of high-yielding and disease and insect resistant varieties of rice. Adoption of green revolution technology was facilitated by: (1) development of irrigation facilities; (2) availability of inorganic fertilizers; (3) benign government policies.

The increase in per capita availability of rice and a decline in the cost of production per ton of output contributed to a decline in real price of rice in international and domestic markets. The unit cost of production is about 20-30% lower from high yielding varieties than for traditional varieties of rice (Yap 1991). The cost of rice is 40% lower now than in 1960s. The decline in food prices has benefited the urban poor and rural landless who spend more than half of their income on food grains.

The Rice Scenario in New Millennium

The world's capacity to sustain favorable food-production population balance has again come under spotlight in view of continued population growth and drastic slowdown in growth of cereal production (Brown 1997). Rice production increased at the rate of 2.5-3.0% per year during 1970s and 1980s. However, during 1990s the growth rate was only 1.5%. According to UN estimates, the world population will grow from 6.3 billion in 2003 to eight billion in 2025. Most of this increase (93%) will occur in developing countries, whose share of population is projected to increase from 78% in 1990s to 83% in 2020.

In spite of all the achievements of green revolution, serious food problems exist in the world. Every 3.6 seconds somebody dies of hunger. Chronic hunger takes the lives of 2400 people every day. Currently there are more than 800 million undernourished people in the developing world, and 300 million children under the age of five die because of hunger and malnutrition, and one out of five babies is born underweight.

Feeding 5 Billion Rice Consumers in 2025

According to various estimates we will have to produce 40% more rice by 2025 to satisfy the growing demand without affecting the resource base adversely. This increased demand will have to be met from less land, with less water, less labor and fewer chemicals. If we are not able to produce more rice from the existing land resources, land hungry farmers will destroy forests and move into more fragile lands such as hillsides and wetlands with disastrous consequences for biodiversity and watersheds. To meet the challenge of producing more rice from suitable lands we need the rice varieties with higher yield potential and greater yield stability.

Increasing the Yield Potential of Rice

Various strategies for increasing the yield potential of rice includes; (1) conventional hybridization and selection procedures, (2) ideotype breeding, (3) heterosis breeding, (4) wide hybridization, (5) genetic engineering

Conventional Hybridization and Selection Procedures

This is the time tested strategy for selecting crop cultivars with higher yield potential. It has two phases. The first phase involves the creation of variability through hybridization between diverse parents. In the second phase desirable individuals are selected on the basis of field observations and yield trials. It has been estimated that on the average about 1.0% increase has occurred per year in the yield potential of rice over a 35 year period since the development of first improved variety of rice, IR8 (Peng et al 2000). The yields of crops where there is enough investment in research have been continuously increased and there is no reason why further increases cannot be attained.

Ideotype Breeding

Ideotype breeding aimed at modifying the plant architecture is a time tested strategy to achieve increases in yield potential. Thus selection for short statured cereals such as wheat, rice, and sorghum resulted in doubling of yield potential. Yield potential is determined by the total dry matter or biomass and the harvest index (HI). Tall and traditional rices had HI of around 0.3 and total biomass of about 12 tons per hectare. Thus their maximum yield was 4 tons per hectare. Their biomass could not be increased by application of nitrogenous fertilizers as the plants grew excessively tall, lodged badly and the yield decreased instead of increasing. To increase the yield potential of topical rice it was necessary to improve the harvest index and nitrogen responsiveness by increasing the lodging resistance. This was accomplished by reducing the plant height through incorporation of a recessive gene *sd1* for short stature.

The first short statured variety IR8, developed at the International Rice Research Institute (IRR) also had a combination of other desirable traits such as profuse tillering, dark green and erect leaves for good canopy architecture and sturdy stems. It responded to nitrogenous fertilizer much better and had a higher biomass (about 18 tons) and HI of 0.45. Its yield potential was 8-9 tons per hectare (Chandler 1969).

To increase the yield potential of rice further, a new plant type was conceptualized in 1988. Modern semi-dwarf rices produce a large number of unproductive tillers and excessive leaf area which cause mutual shading and reduce canopy photosynthesis and sink size, especially when they are grown under direct sowing conditions. To increase the yield potential of these semi-dwarf rices, IRRI scientists proposed further modifications of plant architecture with following characteristics:

- Low tillering,(9-10 tillers for transplanted conditions)
- No unproductive tillers
- 200-250 grains per panicle
- Dark green, thick and erect leaves
- Vigorous and deep root system

This proposed ideotype became the "New Plant Type" (NPT) highlighted in IRRI's strategic plan (IRRI 1989) and breeding efforts to develop NPT were initiated in 1990. The objective was to develop improved germplasm with 15-20% higher yield than the existing high yielding varieties. Numerous breeding lines with desired ideotype were developed (Khush 1995) and shared with the national rice improvement programs. Three NPT lines have been released in China and one in Indonesia. Other NARS are evaluating and further improving NPT lines.

Heterosis Breeding

Yield improvement in maize has been associated with hybrid development. Yields of maize in USA were basically unchanged from mid 19th century until 1930 and accelerated after introduction of commercial double cross hybrids. The subsequent replacement of double cross hybrids by single cross hybrids in 1960 is associated with second acceleration in maize yields. The average yield advantage of hybrids versus cultivars is approximately 15% (Tallenaar 1994).

Rice hybrids with a yield advantage of about 10-15% over best inbred varieties were introduced in China in mid 1970s and are now planted to about 45% of the riceland in that country. Rice hybrids adapted to tropics have now been bred at IRRI and by NARS and show similar yield advantage. The increased yield advantage of tropical rice hybrids is due to increased biomass, higher spikelet number and to some extent higher grain weight. Increased adoption of hybrids in the tropics should contribute to increased productivity.

Wide Hybridization

Crop gene pools are widened through hybridization of crop cultivars with wild species, weedy races as well as intrasubspecific crosses. Such gene pools are exploited for improving many traits including yield. For example Lawrence and Fry (1976) reported that a quarter of lines from BC_2-BC_4 segregants from the *Avena Sativa* x *Avena Sterilis* crosses were significantly higher in grain yield than the cultivated recurrent parent. Nine lines from this study when tested over years and sites had agronomic traits similar to the recurrent parent and 10-29% higher grain yield. The higher yield potential of these interspecific derivatives was attributed to higher vegetative growth rates or early seedling vigor.

Xiao et al (1996) reported that some backcross derivates from a cross between an *Oryza rufipogon* accession from Malaysia and cultivated rice, out yielded the recurrent parent by as much as 18%. They identified two QTL from wild species with major contribution to yield increase. These QTL are now being transferred to several modern semi-dwarf varieties.

Genetic Engineering

Since protocols for rice transformation are well established (Christou et al. 1991); it is now possible to introduce single alien genes that can selectively modify yield determining processes. In several crop species, incorporation of “stay green” trait or slower leaf senescence has been a major achievement of breeders in the past decade (Evans 1993). In some genotypes with slower senescence (stay green), the rubico degradation is slower which results in longer duration of canopy photosynthesis and higher yields. The onset of senescence is controlled by complement of external and internal factors. Plant hormones such as ethylene and abscisic acid promote senescence. While cytokinins are senescence antagonists. Therefore, over production of cytokinins can delay senescence. The ipt gene from *agrobacterium tumefacions* encoding an *isopentenyl transferase* (Akiyoshi et al. 1984) was fused with sensecence-specific promoter, SAG 12 (Gan and Amasino 1995) and introduced into tobacco plants. The leaf and floral senescence in the transgenic plant was markedly delayed, biomass and seed yield was increased but other aspects of plant growth and development were normal. This approach appears to have great potential in improving the crop yields through slowing the senescence and rubico degradation and thus improving canopy photosynthesis.

C4 plants such as maize and sorghum are more productive as compared to C3 rice and wheat, because C4 plants are 30-35% more efficient in photosynthesis. Ku et al (1999) and Mutsuoka el al (2001) are trying to alter the photosynthesis of rice from C3 to C4 pathway by introducing cloned genes from maize which regulates the production of enzymes responsible for C4 synthesis. If successful, the yield potential of rice may increase 30-35%.

Breeding for Durable Resistance

Full yield potential of modern rice varieties is not realized because of the toll taken by the attack of disease and insect organisms. It is estimated that diseases and insects cause yield losses of up to 25% annually. Genetic improvement to incorporate durable resistance to pests is the preferred strategy to minimize these losses. There is no cost to farmers and resistant cultivars are easily adopted and disseminated unlike “knowledge based” technologies. Also concern for the environment has become an important public policy issue and pest management methods that minimize the use of crop protection chemicals are increasingly finding favor.

Diverse sources of resistance to major diseases and insects have been identified and rice varieties with multiple resistances to diseases and insects have been developed. However, no sources of resistance to sheath blight are available and there is paucity of donors for resistance to virus diseases and stem borer. Recent breakthroughs in cellular and molecular biology have provided tools to develop more durably resistant cultivars and to overcome the problem of lack of donors for resistance.

Wide Hybridization for Disease and Insect Resistance

Wild species of rice are a rich source of genes for resistance breeding. For example, none of the cultivated rice was found to be resistant to grassy stunt. *Oryza nivara*, a wild species closely related to cultivated rice was found to be resistant and the dominant gene for resistance was transferred to improved germplasm through backcrossing. This gene for resistance has been incorporated into many widely grown varieties. When genes are to be transferred from more distantly related species, special techniques such as embryo rescue are employed to reproduce inter-specific hybrids. Jena and Khush (1990) transferred genes for resistance to three biotypes of brown plant hopper from *O.officinalis* to an elite breeding line. Multani et al (1994) transferred genes for resistance to brown plant hopper from *O.australiensis* to cultivated rice. Similarly genes for resistance to blast and bacterial blight have been transferred form *O.minuta* to improved rice germplasm (Brar and Khush 1997)

Molecular Marker Assisted Breeding

Numerous genes for disease and insect resistance are repeatedly transferred from one varietal background to the other. Most genes behave in dominant or recessive manner and require time consuming efforts to transfer. Sometimes the screening procedures are cumbersome and expensive and require large field space. If such genes can be tagged by tight linkage with molecular markers, time and money can be saved in transferring these genes from one varietal background to another. The presence or absence of the associated molecular marker indicates at an early stage, the presence or absence of the desired target gene. A molecular marker very closely linked to the target gene can act as a “tag” which can be used for indirect selection of target gene.

Two of the most serious and widespread diseases in rice production are rice blast caused by the fungus *pyrcularia oryzae*, and bacterial blight caused by *Xanthomonas oryzae pv.oryzae*.

Development of durable resistance to these diseases is the focus of a coordinated effort at IRRI using molecular marker technology. Efforts to detect markers closely linked to bacterial blight resistance genes have taken advantage of the availability of near isogenic lines having single genes for resistance. Segregating populations were used to confirm co-segregation between RFLP markers and genes for resistance. Protocols for converting RFLP markers into PCR based markers and using the PCR markers in marker-aided selection have been established (Zeng et al 1995). The PCR markers were also used for pyramiding genes for resistance to bacterial blight. Thus *xa4, x5, xa13, and Xa21* were combined into same breeding line (Huang et al 1997). The pyramided lines showed a wider spectrum and higher level of resistance than lines with only a single gene for resistance. MAS has also been employed for moving genes from pyramided lines into new plant type (Sanchez et al. 2000) as well as into improved varieties grown in India (Singh et al 2001).

Genetic Engineering

Protocols for rice transformation have been developed which allow transfer of foreign genes from diverse biological systems into rice. Direct DNA transfer methods such as protoplast based (Datta et al. 1990) and biolistic (Christou et al. 1991) as well as *Agrobacterium*-mediated (Hei et al 1994) are being used for rice transformation. Major targets for rice improvement through transformation are disease and insect resistance.

As early as 1987, genes encoding for toxins from *Bacillus thuringiensis* (BT) were transferred to tomato, tobacco and potato, where they provided protection against Lepidoptern insects. A major target for BT deployment in transgenic rice is the yellow stem borer. This pest is widespread in Asia and causes substantial crop losses. Improved rice cultivar are either susceptible to the insect or have only partial resistance. Thus *BT* transgenic rice has much appeal for controlling the stem borer. Codon optimized *BT* genes have been introduced into rice and show excellent levels of resistance in the laboratory and greenhouse (Datta et al 1997). *Bt* rices have also been tested under field conditions in China (Tu et al. 2000) and have excellent resistance to diverse populations of yellow stem borer. Besides *BT* genes, other genes for insect resistance such as those for proteinase inhibitors, *α*-amylase inhibitors and lectins are also beginning to receive attention. Insects use diverse proteolytic or hydrolytic enzymes in their digestive gut for the digestion of food proteins and other food components. Plant derived proteinase inhibitors or α-amylase inhibitors are of particular interest because these inhibitors are a part of the natural plant defense system against insect predation. Xu el al (1996) reported tansgenic rice carrying cowpea trypsin inhibitor (*Cpti*) gene with enhanced resistance against striped stem borer and pink stem borer.

Several viral diseases cause serious yield losses in rice. A highly successful strategy termed coat protein (CP) mediated protection has been employed against certain viral diseases such as tobacco mosaic virus in tobacco and tomato. A coat protein gene from rice strip virus was introduced into two japonica varieties by electroporation of protoplasts (Hayakawa et al 1992). The resultant transgenic plants expressed CP at high level and exhibited a significant level of resistance to virus infection and the resistance was inherited to the progenies.

Breeding for Abiotic Stress Tolerance

A series of stresses such as drought, excess water, mineral deficiencies and toxicities in soil and unfavorable temperatures affect rice productivity. The progress in developing crop cultivars for tolerance to abiotic stresses has been slow because of lack of knowledge of mechanisms of tolerance, poor understanding of inheritance of resistance or tolerance, low heritability and lack of efficient techniques for screening the germplasm and breeding materials. Nevertheless, rice cultivars with varying degrees of tolerance to abiotic stresses have been developed.

Rainfed rice is planted to about 40 million hectares worldwide. Vast areas suffer from drought at some stage of growth cycle. QTL for various component traits of drought tolerance have been mapped (Champoax et al 1995) and the information is being utilized to develop improved cultivars with drought tolerance.

Genetic engineering techniques hold great promise for developing rice with drought tolerance. Garg et al (2002) introduced *ots A* and *ots B* genes for trehalose biosynthesis from *Escherichia coli* into rice and transgenic rices accumulated trehalose at 3-10 times that of nontransgenic controls. Trehalose is a nonreducing disaccharide of glucose that function as compatible solute in the stabilization of biological structures under abiotic stress . The transgenic rice lines had increased tolerance for abiotic stresses such as drought and salinity. Accumulation of sugar alcohols is a widespread response that may protect the plants against environmental stress through osmoregulation. Mannitol is one of the sugar alcohols commonly found in plants. Tobacco plants lacking mannitol were transformed with a bacterial gene *mtlD* encoding mannital (Tarczynski et al 1992). Mannitol concentrations exceeded 6 μ mol/g (fresh weight) in the leaves and in the roots of some transformants, whereas this sugar alcohol was not detected in these organs of control tobacco plants. Growth of plants from control and mannitol-containing lines in the absence and presence of sodium chloride (NACL) in culture solution was analyzed. Plants containing mannitol had an increased ability to tolerate salinity (Tarcynski et al 1993). After 30 days of exposure under concentrations of 20 m Nacl in culture solution, transformed plants increased in height a mean of 80% whereas control plants increased only a mean of 22% over the same interval. This approach is worth trying in rice.

In some areas rice crop suffers from floods when it is submerged under water for up to 10 days. Rice cultivars cannot survive such prolonged submergence. A few rice cultivars have been identified which survive submergence for 8-10 days. Using FR13A one of the submergence tolerant donors, improved rice cultivars with submergence tolerance have been developed (MacKill et al. 1993).

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